United States Nuclear Regulatory Commission

Protecting People and the Environment

PRA and Risk-Informed Decisionmaking at the NRC: Status and Challenges

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Prelude

Risk, PRA, and risk-informed decisionmaking

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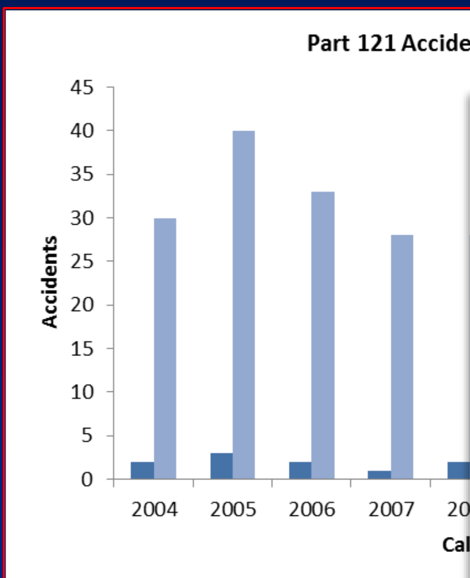
A Common Definition of "Risk"

$$\text{Risk} \equiv \sum_i p_i \times C_i$$

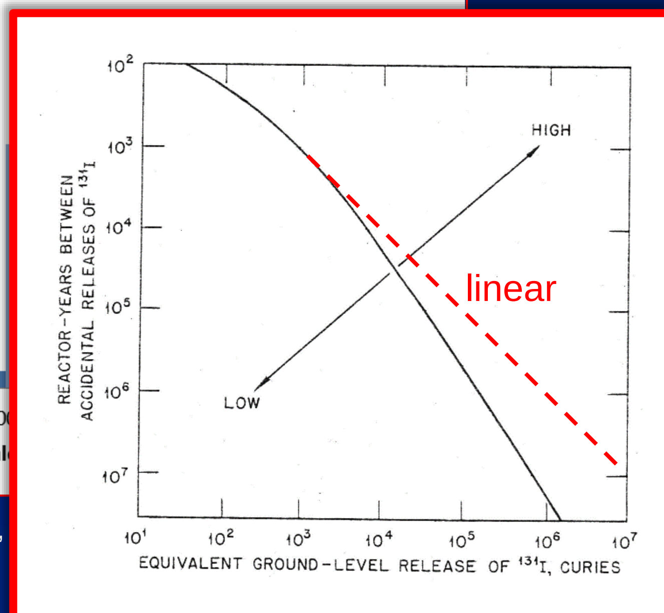
Decision support concerns:

- Purely quantitative
- Average value, equates
  - Low-probability/high-consequence
  - High-probability/low-consequence

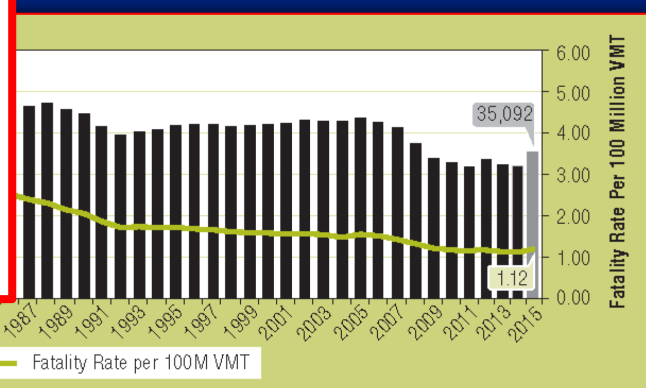
Low-Probability/High Consequence vs. High-Probability/Low Consequence



National Transportation Safety Board, (http://www.ntsb.gov/investigations/)



Adapted from Farmer, F.R., “Reactor safety and siting: a proposed risk criterion,” *Nuclear Safety*, **8**, 539-548(1967).



From “Traffic Safety Facts: Research Note,” U.S. Dept. of Transportation, 2016.

The Triplet Definition of "Risk" (Kaplan and Garrick, 1981)

Risk ≡ $\{s_i, C_i, p_i\}$

- What can go wrong?
- What are the consequences?
- How likely is it?

Features

- Vector, not scalar
- Qualitative and quantitative
- Differences across accident spectrum

Probabilistic Risk Assessment (PRA)

- Answers the risk triplet questions
  - Addresses entire system
  - Includes event tree and fault tree analysis
- Supports decisions
  - Defined problem
  - Realistic
  - Practical
  - Treats uncertainties

Risk-Informed Regulatory Decisionmaking

Consider risk insights together with other factors

Risk-Informed ≠ Risk-Based

Remainder of Talk

- PRA at the NRC
- Example Applications
- PRA Pointers/Reminders
- Current Challenges
- Closing Thoughts

Key Messages

- Risk is the answer to three questions
  - What can go wrong?
  - What are the consequences?
  - How likely is it?
- NRC uses PRA to support regulatory decision making
  - Risk-informed (not risk-based) decisionmaking
  - All regulatory functions
- Technical and implementation challenges are spurring research and other activities

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PRA at the NRC

Who we are, how we use risk information, and why

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A PRA Timeline

1995 PRA Policy Statement

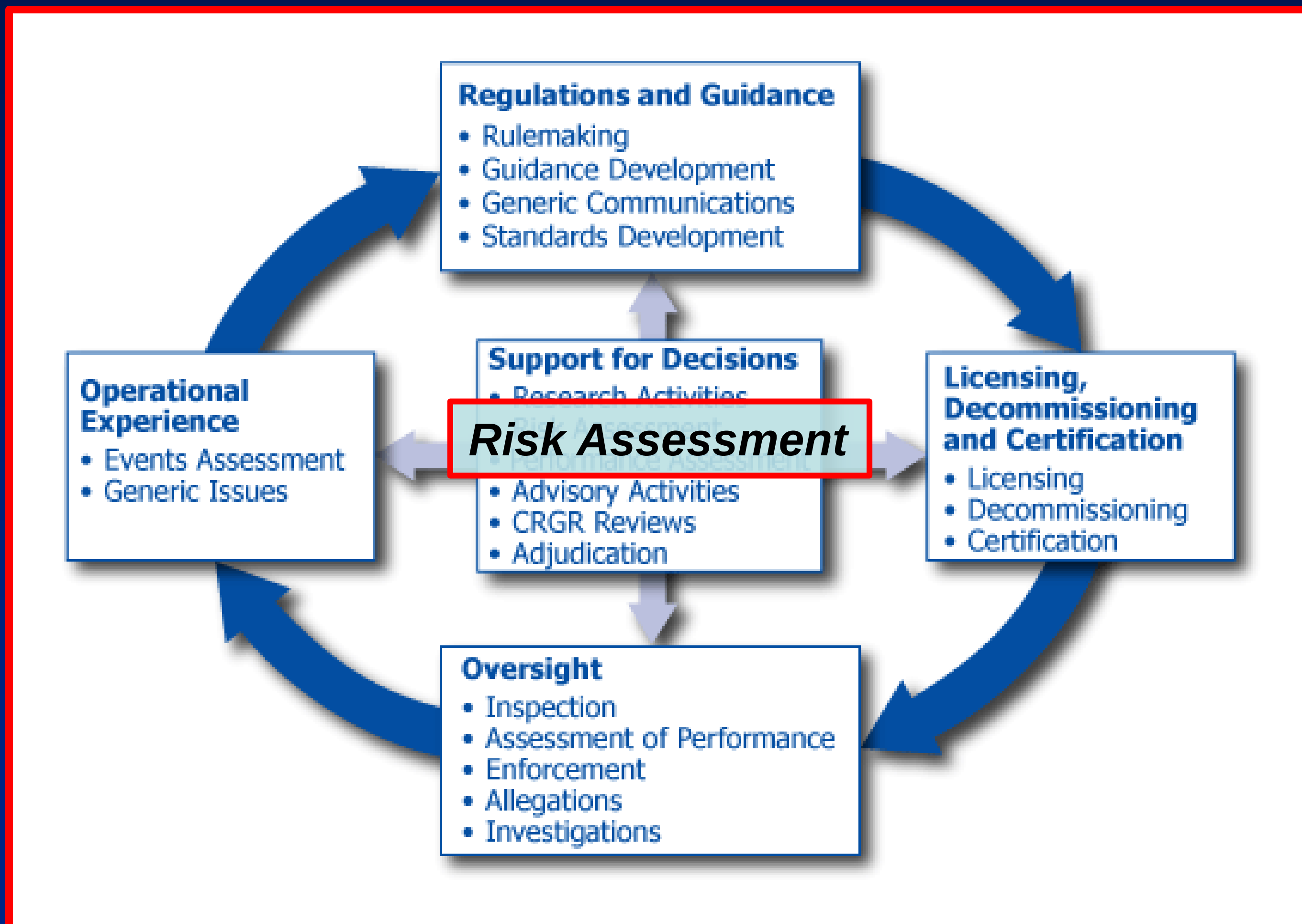
- Increase use of PRA technology in all regulatory matters
  - Consistent with PRA state-of-the-art
  - Complement deterministic approach, support defense-in-depth philosophy
- Benefits:

  (1) Considers broader set of potential challenges

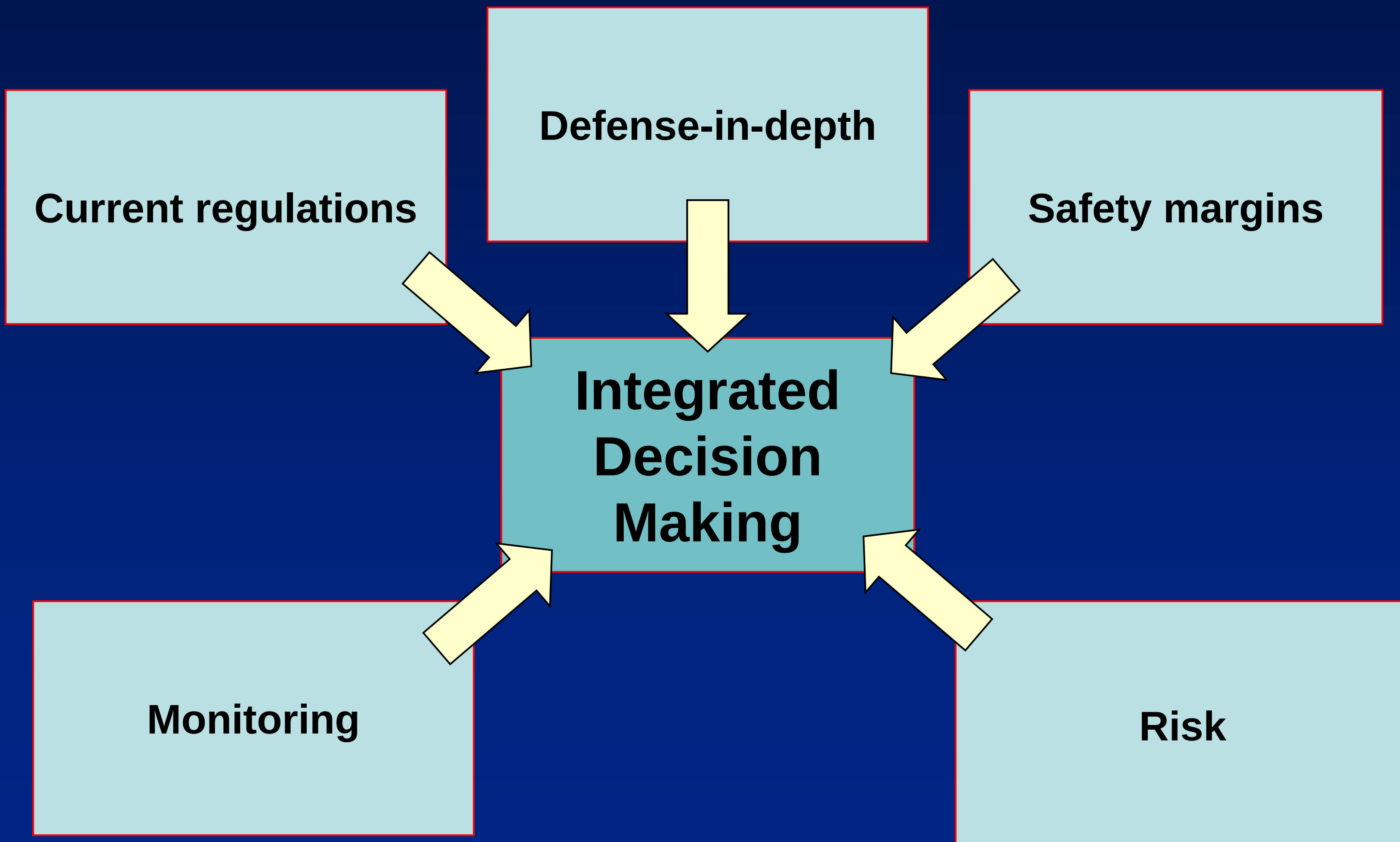
  (2) Helps prioritize challenges

  (3) Considers broader set of defenses

All regulatory matters



Complementing deterministic approach



Adapted from RG 1.174

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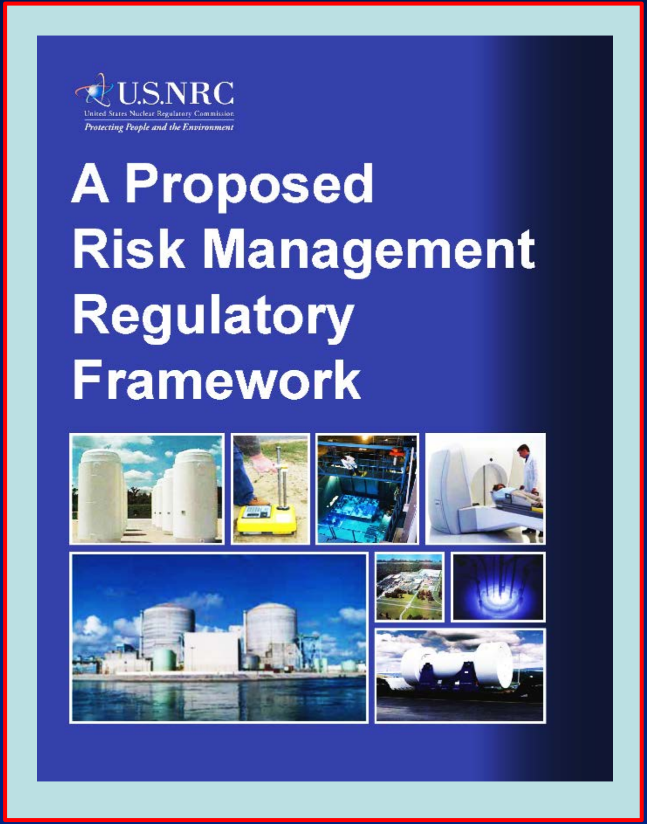
PRA Applications

Some examples of PRA uses

Risk Management - General

- Decisions
  - Industry-wide and license-specific
  - Operating reactors: applications are voluntary
  - New reactors: PRAs required for design certification and licensing
- NUREG-2150: proposal to increase use of risk information



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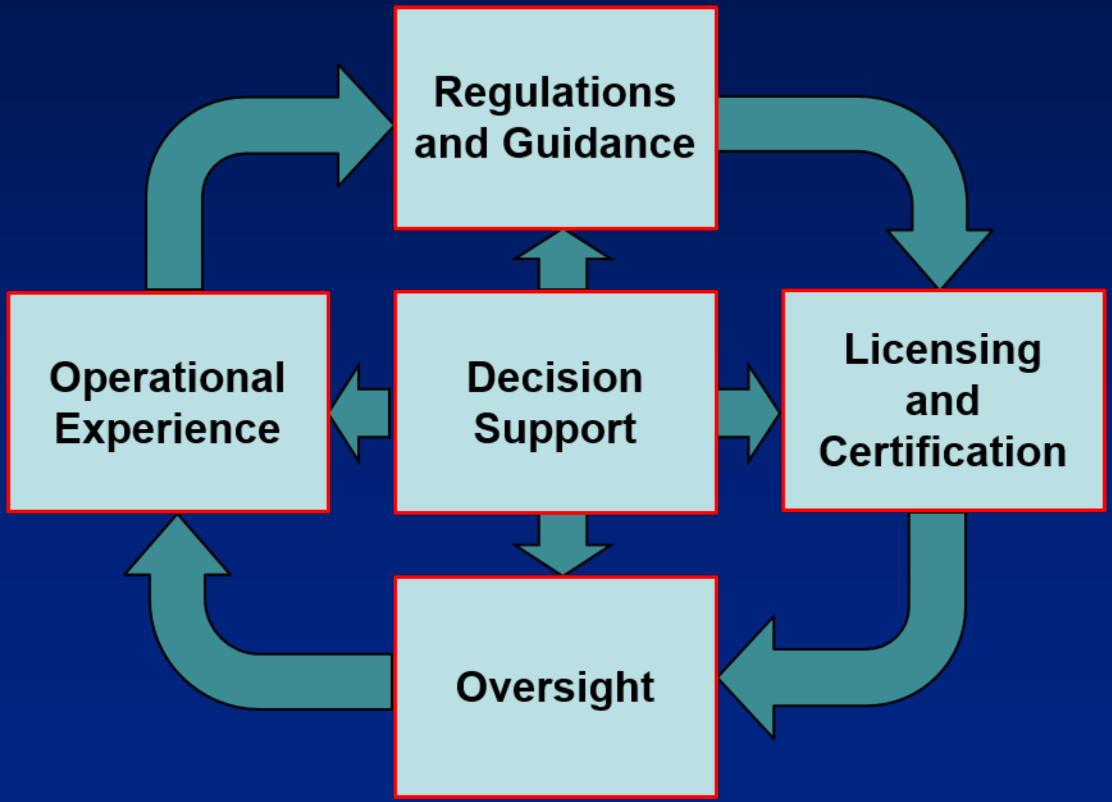
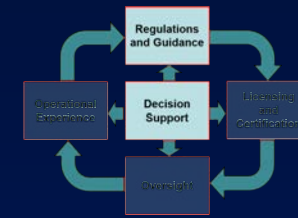
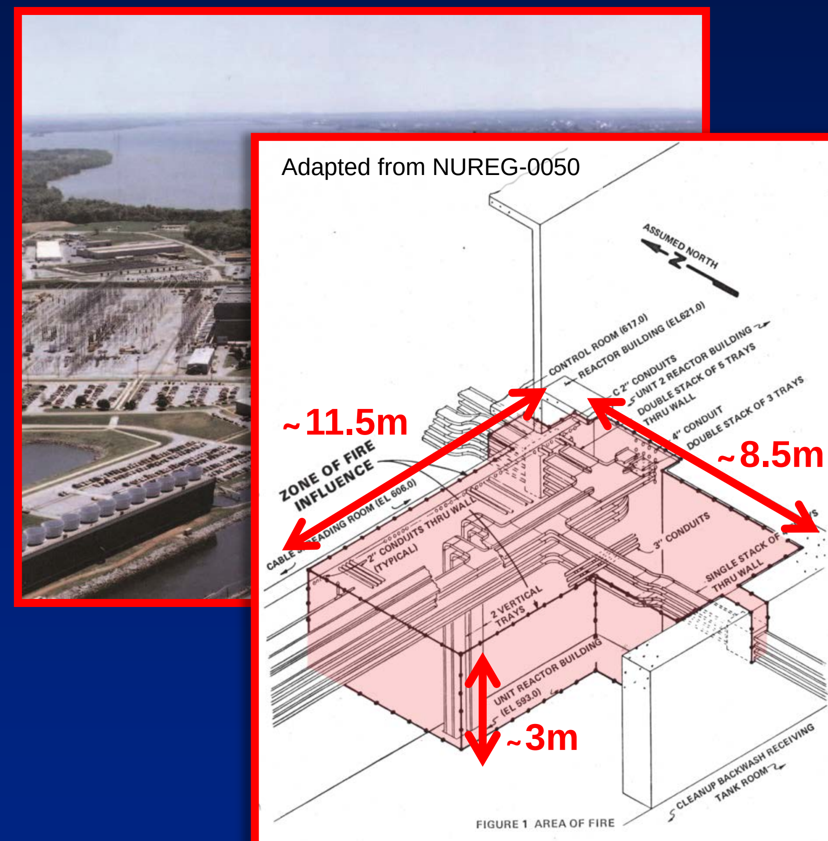
NRC Applications of Risk Information

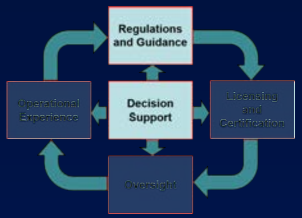




Fire Protection ("NFPA 805")

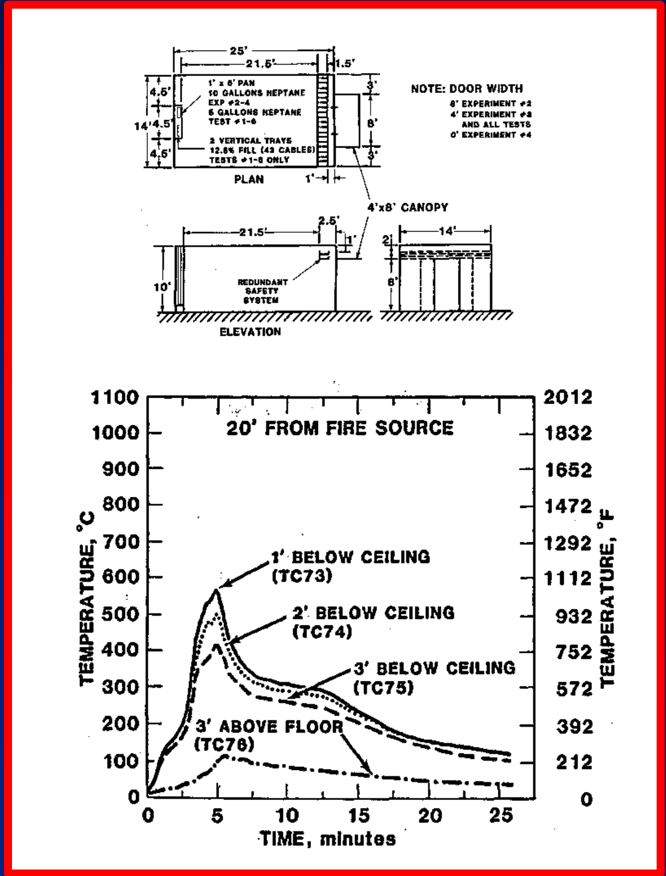
- Browns Ferry Nuclear Power Plant fire (3/22/75)
- Candle ignited foam penetration seal, initiated cable tray fire; water suppression delayed; complicated shutdown
- Second-most challenging event in U.S. nuclear power plant operating history
- Spurred changes in requirements and analysis



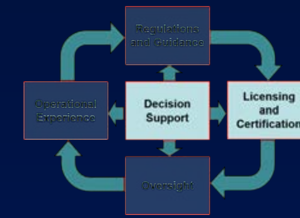


Fire Protection ("NFPA 805")

- Post-Browns Ferry deterministic fire protection (10 CFR Part 50, App R)
  - 3-hour fire barrier, OR
  - 20 feet separation with detectors and auto suppression, OR
  - 1-hour fire barrier with detectors and auto suppression
- Risk-informed, performance-based fire protection (10 CFR 50.48(c), NFPA 805)
  - Voluntary alternative to Appendix R
  - Deterministic and performance-based elements
  - Changes can be made without prior approval; risk must be "acceptable"

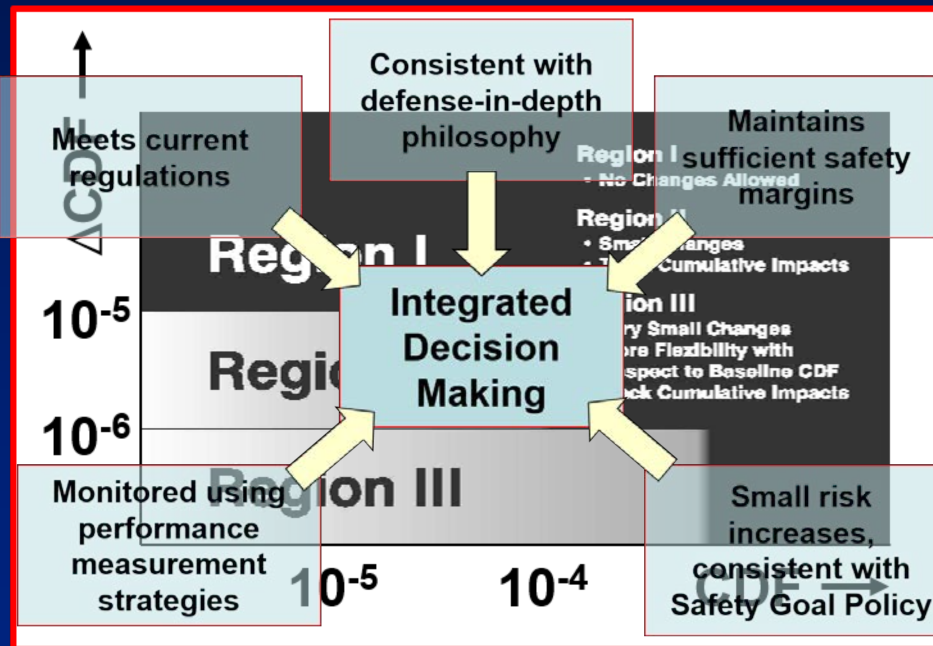


From Cline, D.D., et al., "Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R," NUREG/CR-3192, 1983.

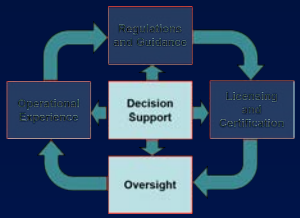


Changes in Plant Licensing Basis (RG 1.174)

- Voluntary changes: licensee requests, NRC reviews
- Small risk increases may be acceptable
- Change requests may be combined
- Decisions are risk-informed



U.S. Nuclear Regulatory Commission, “An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant Specific Changes to the Licensing Basis,” Regulatory Guide 1.174, Revision 2, 2011.

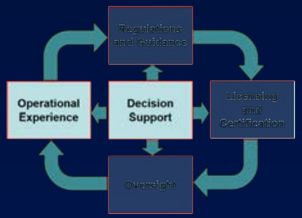


Reactor Oversight Program

- Inspection planning
- Determining significance of findings
  - Characterize performance deficiency
  - Use review panel (if required)
  - Obtain licensee perspective
  - Finalize
- Performance indicators

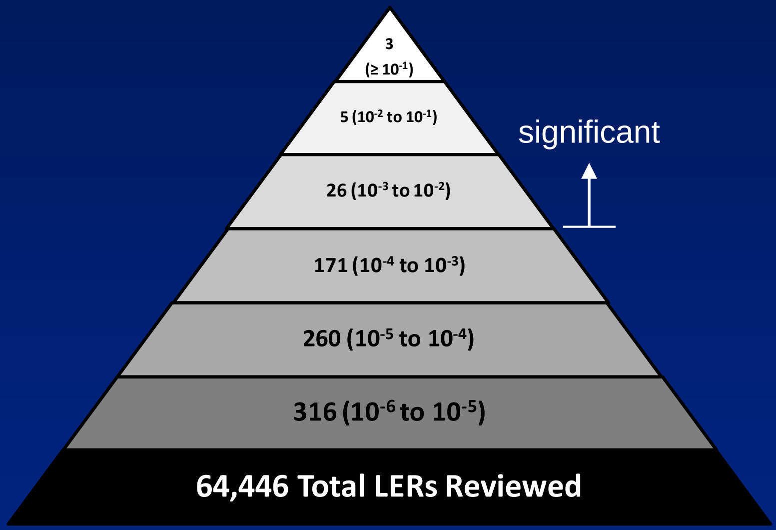
$\Delta CDF < 1E\text{-}6$ $\Delta LERF < 1E\text{-}7$
$1E\text{-}6 < \Delta CDF < 1E\text{-}5$ $1E\text{-}7 < \Delta LERF < 1E\text{-}6$
$1E\text{-}5 < \Delta CDF < 1E\text{-}4$ $1E\text{-}6 < \Delta LERF < 1E\text{-}5$
$\Delta CDF > 1E\text{-}4$ $\Delta LERF > 1E\text{-}5$

CDF = Core damage frequency
LERF = Large early release frequency



Accident Sequence Precursor Program

- Program recommended by WASH-1400 review group (1978)
- Provides risk-informed view of nuclear plant operating experience
  - Conditional core damage probability (events)
  - Increase in core damage probability (conditions)
- Supported by plant-specific Standardized Plant Analysis Risk models



Licensee Event Reports 1969-2010
(No significant precursors since 2002)

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Keep in mind…

General PRA pointers and observations

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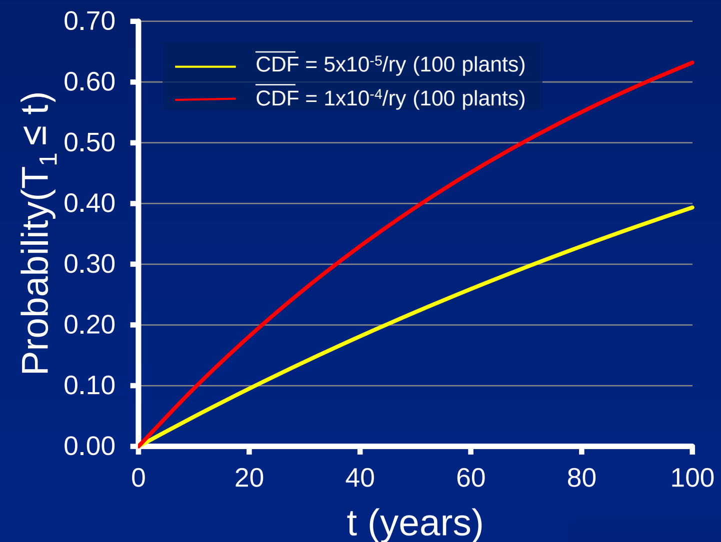
Core Damage Frequency (CDF) is a metric

- Governing equation

$$P\{\text{N CD events in } (0,T)|\text{CDF}\} = \frac{(\text{CDF}\cdot T)^N}{N!} e^{-\text{CDF}\cdot T}$$

- Key assumptions
  - Independent events
  - No aging effects
- Clusters ≠> dependence



"P" in PRA reflects state of knowledge

P{X|C,H}

- P = Probability
- X = Proposition of concern (e.g., Plant X will have core melt in next 20 years)
- C = Conditions of assessment (e.g., key assumptions)
- H = State of knowledge:
  - Includes basic science/engineering, model predictions, empirical data, expert judgment
  - Dependent on assessor(s)

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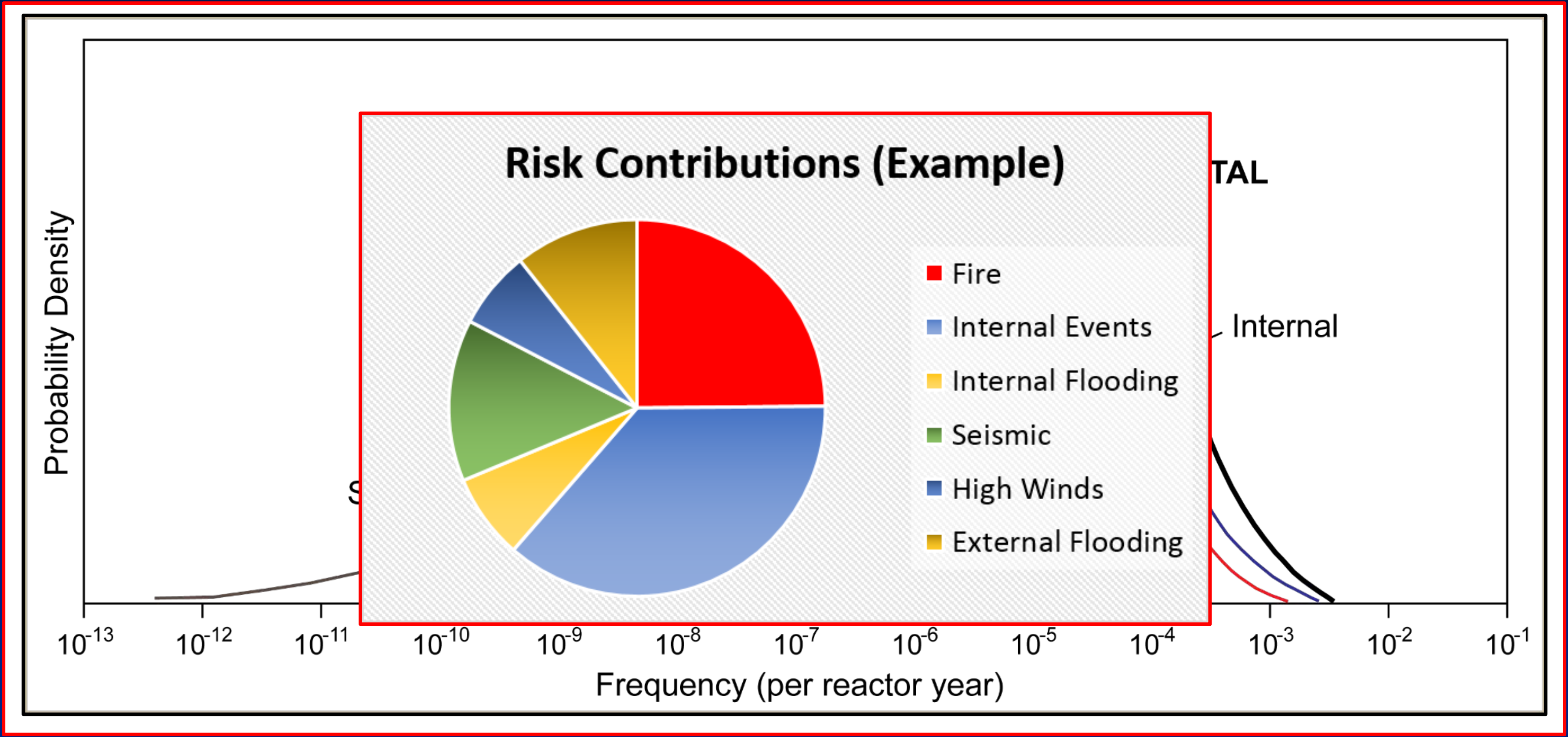
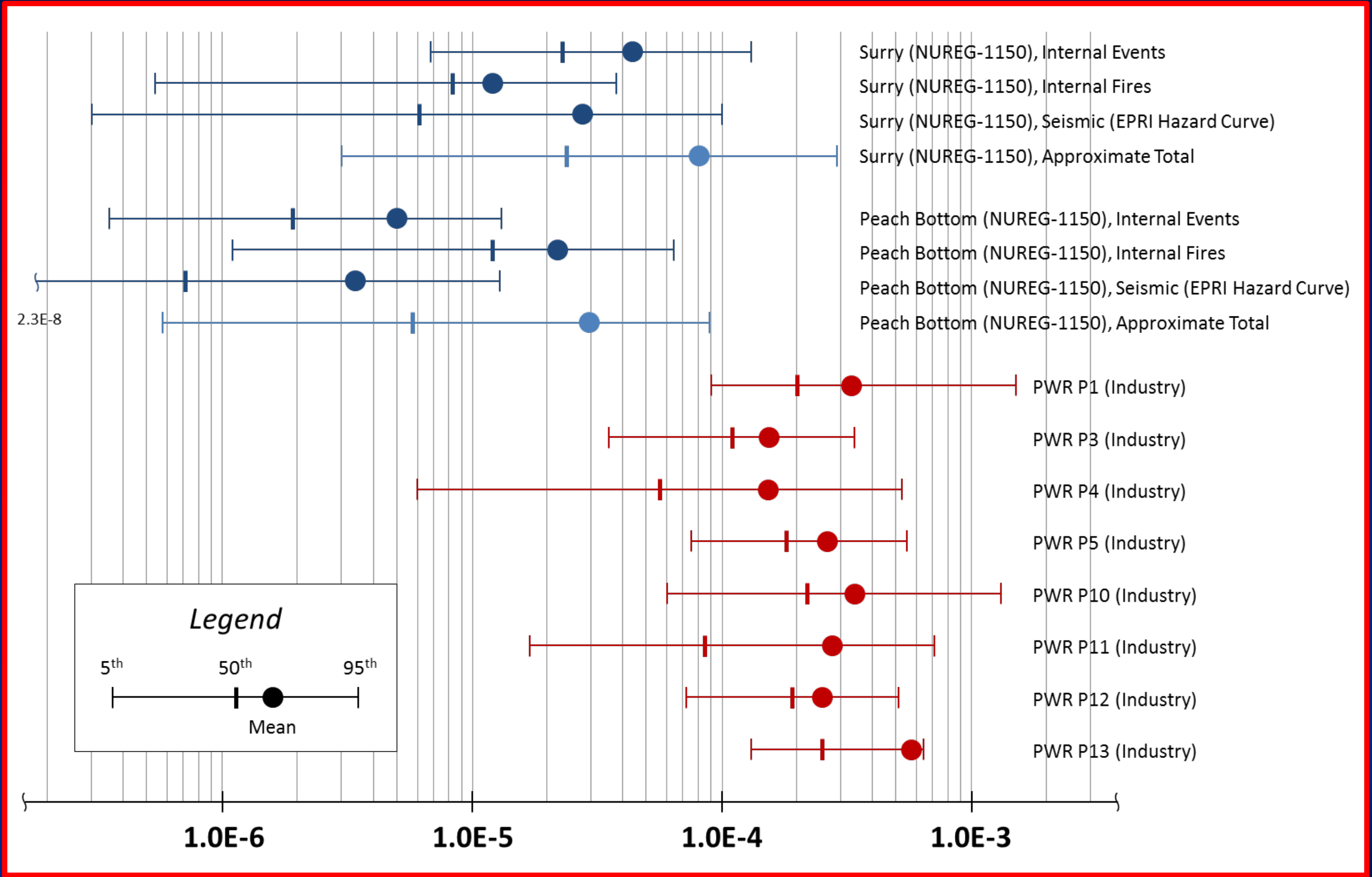
Multiple hazards can be important



Uncertainties often ≥ order of magnitude



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Some Challenges

Improving the technology and system

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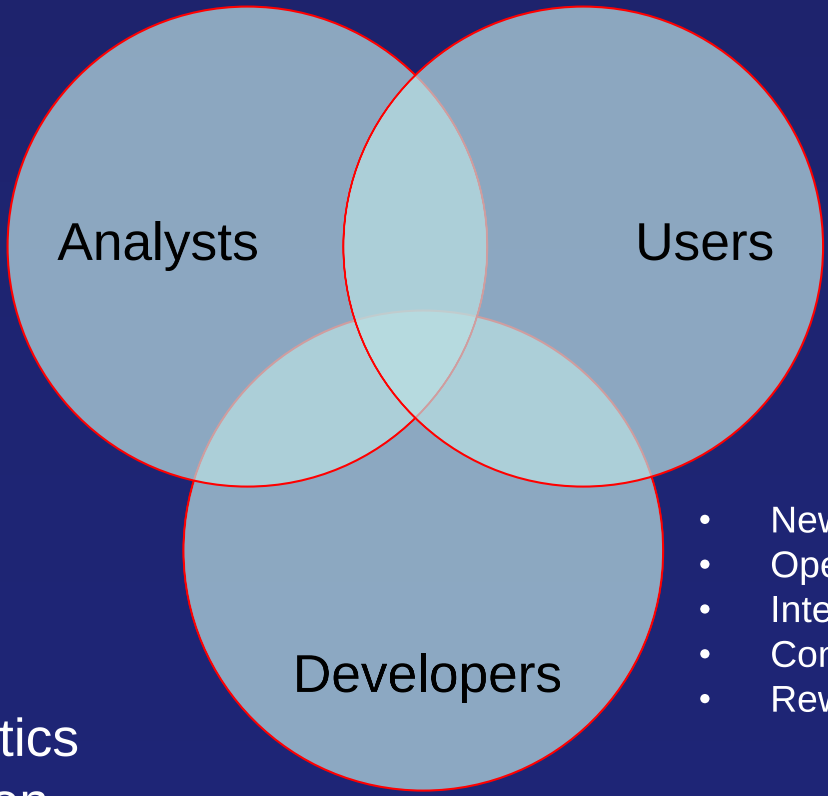
Example Challenges

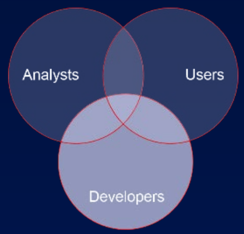
- Data
- Bounding/screening
- Guidance
- “Holes”
- Integration
- Imagination



- Understanding
- Uncertainties
- Heterogeneity and aggregation
- Confidence
- Other Factors (e.g., DID, safety margins)
- Stakeholders

- New science/engineering
- Operational experience
- Intended users/applications
- Computational limits
- Rewards

- Time
- Resources
- Biases/heuristics
- Communication

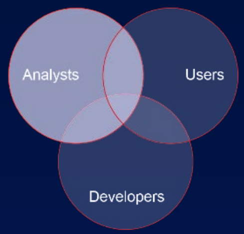


New Experiments and Analyses

- Hig
- Aqu … ater
- Sta … A)

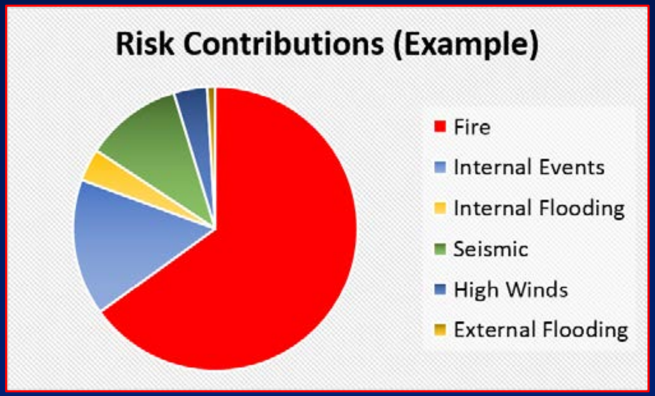
480V switchgear, 42 kA, 8 sec

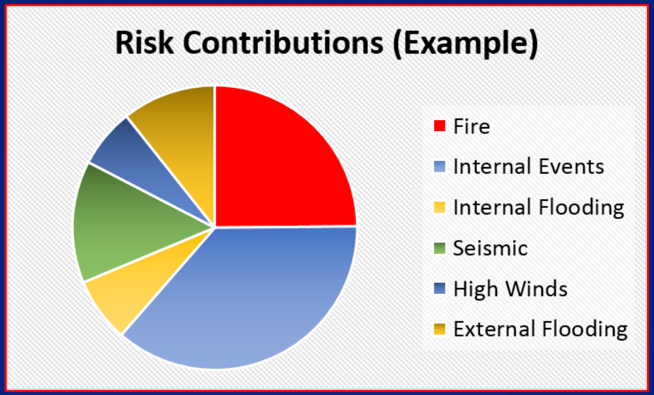
Project information: http://www.oecd-nea.org/jointproj/heaf.html

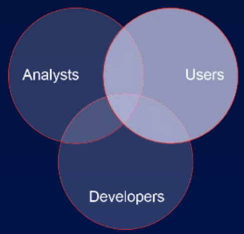


Bounding/Screening

- Needed to focus analysis on important scenarios
- Technical needs
  - Fundamental science/engineering
  - PRA methods, models, tools, data
  - Guidance
- Potential concerns
  - Overestimate total risk
  - Distort risk profile







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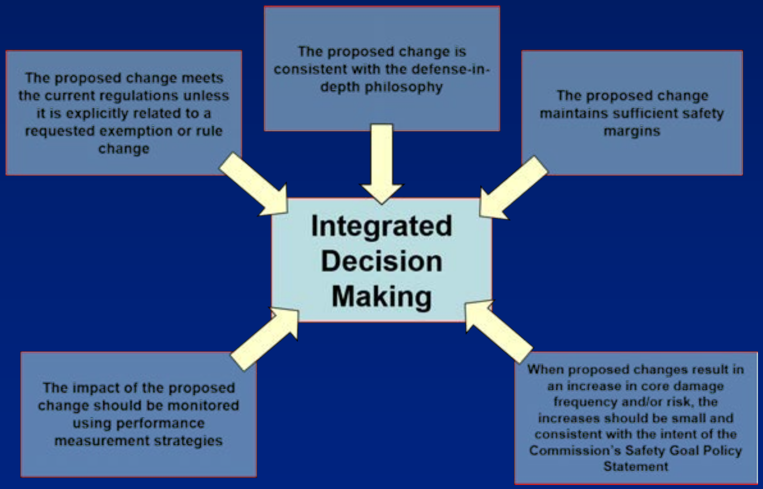
Stakeholder Views

NRC Risk-Informed Steering Committee

- Provides strategic direction to advance use of risk-informed decisionmaking
- Formed October 2013
- Public meetings
- Coordinated working groups
  - Technical adequacy (including new methods approval)
  - Uncertainty in decision making (including aggregation)
  - Credit for mitigating strategies



Adapted from RG 1.174

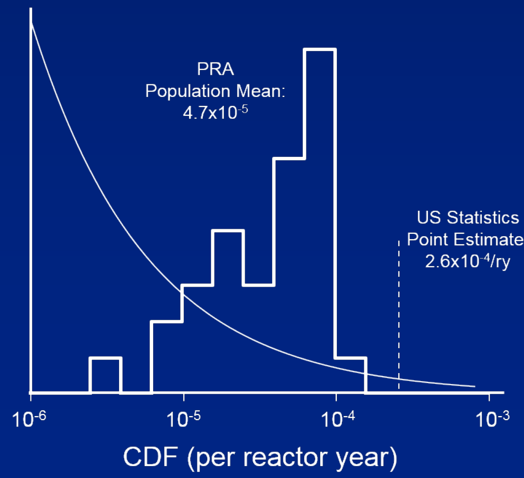
Closing Thoughts

Post-Fukushima critiques, key messages, references

Post-Fukushima PRA Discussions

PRA Critiques

- PRAs did not predict observed scenario – "failure of imagination"
- Global statistics "prove" PRAs underestimate risk



NRC Perspectives

- PRAs
  - identify and quantify possibilities; do not "predict"
  - look beyond the design basis and past operational experience
  - Provide framework to search for failure scenarios
- Global statistical estimates
  - assume exchangeability
  - neglect key information needed for regulatory decisionmaking
  - can spur examination of models

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Key Messages

- Risk is the answer to three questions
  - What can go wrong?
  - What are the consequences?
  - How likely is it?
- NRC uses PRA to support regulatory decision making
  - Risk-informed (not risk-based) decisionmaking
  - All regulatory functions
- Technical and implementation challenges are spurring research and other activities

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For Further Reading*

- USNRC, "A Proposed Risk Management Regulatory Framework," NUREG-2150, 2012.
- USNRC, "Use of Probabilistic Risk Assessment Methods in Nuclear Activities: Final Policy Statement," Federal Register, Vol. 60, p. 42622 (60 FR 42622), August 16, 1995.
- USNRC, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant Specific Changes to the Licensing Basis," Regulatory Guide 1.174, Revision 2, 2011.
- USNRC, "No Undue Risk: Regulating the Safety of Operating Nuclear Power Plants," NUREG/BR-0518, 2014.
- USNRC, "Probabilistic Risk Assessment and Regulatory Decision Making: Some Frequently Asked Questions," NUREG-2201, in preparation.
- Kaplan, S. and B.J. Garrick, "On the quantitative definition of risk," *Risk Analysis*, **1**, 11-37(1981).

*Most of these references can be found at www.nrc.gov

NRC Information

- Website: www.nrc.gov
- Agencywide Document Access and Management System (ADAMS): http://adams.nrc.gov/wba/
- Jobs (USAJOBS): http://www.nrc.gov/about-nrc/employment/apply.html
- Status of Risk-Informed Activities: SECY-15-0135 (“Annual Update of the Risk-Informed Activities Public Web Site,” ADAMS ML15267A387, October 27, 2015)

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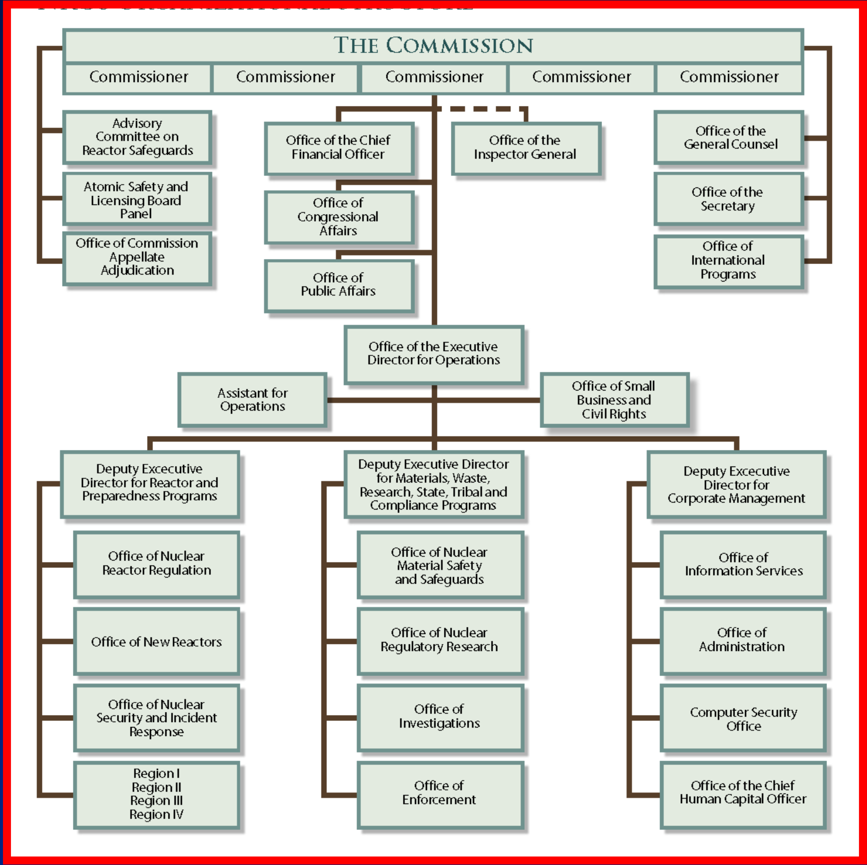
Additional Slides

NRC Organization

- Headquarters + 4 Regional Offices
- 5 Commissioners
- ~3350 staff (FY 2016)
- Annual budget ~$1B
- Website: www.nrc.gov
- Information Digest: NUREG-1350 V27



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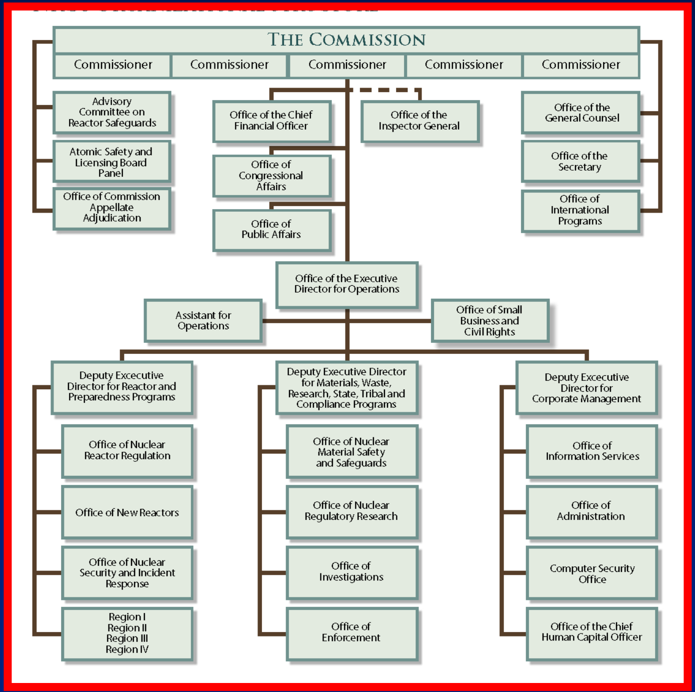
NRC PRA Work and Interactions

- NRC (HQ and Regions)
  - Analysts
  - Reviewers
  - Policy and decision makers
- National Laboratories
- Private Firms
- Universities
- Cooperating Organizations
  - Other government agencies
  - Industry (licensees, owners groups, R&D)
  - International (IAEA, OECD/NEA)
- Standards Organizations
- Public
  - Industry
  - PRA community
  - General public



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NRC Mission

"The U.S. Nuclear Regulatory Commission licenses and regulates the Nation's civilian use of radioactive materials to protect public health and safety, promote the common defense and security, and protect the environment."

- NUREG-1614 (NRC Strategic Plan)

Regulatory Approach

Standard*

“Reasonable assurance of adequate protection”

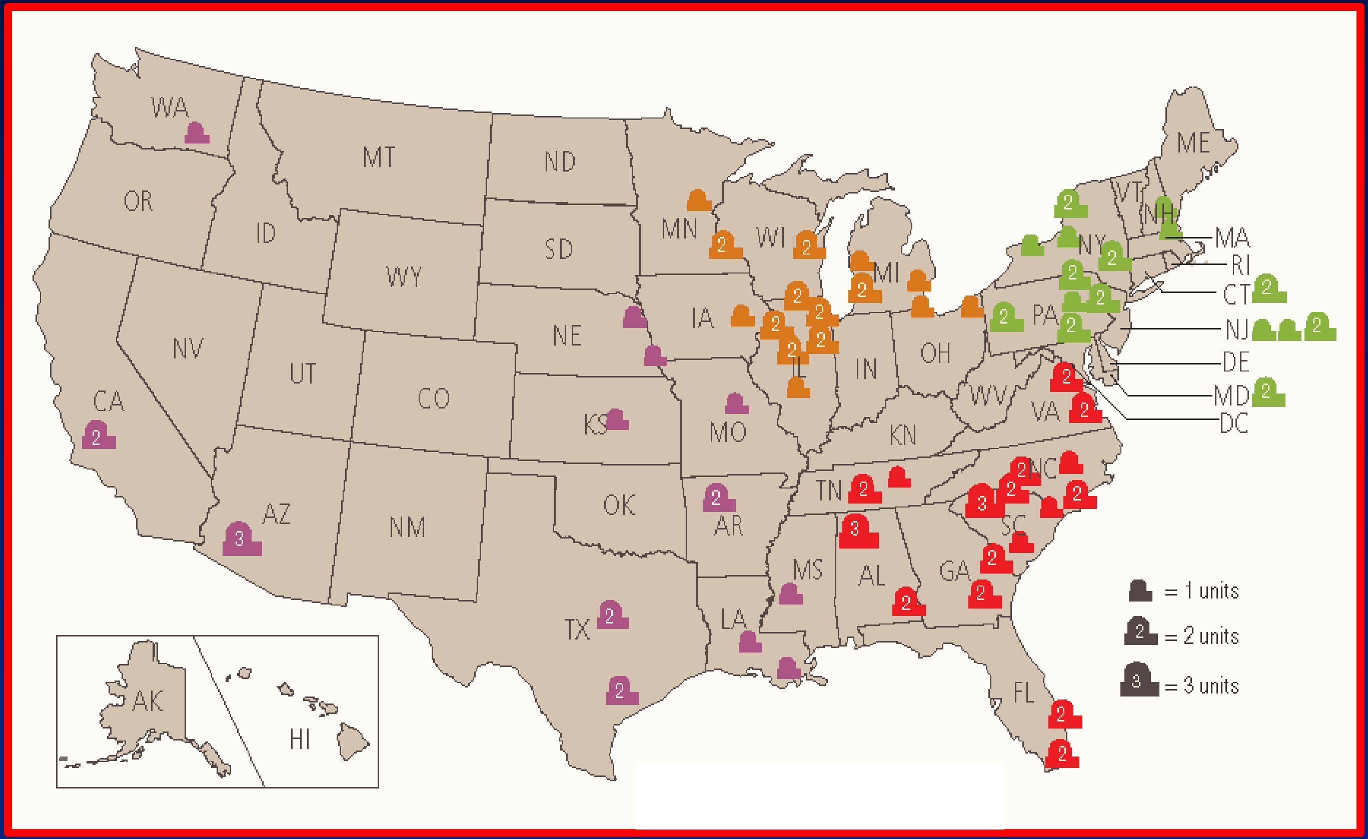
Principles**

- Independence
- Openness
- Efficiency
- Clarity
- Reliability

* When granting, suspending, revoking, or amending licenses or construction permits. (Atomic Energy Act of 1954, as amended – see NUREG-0980, v1, n7, 2005)

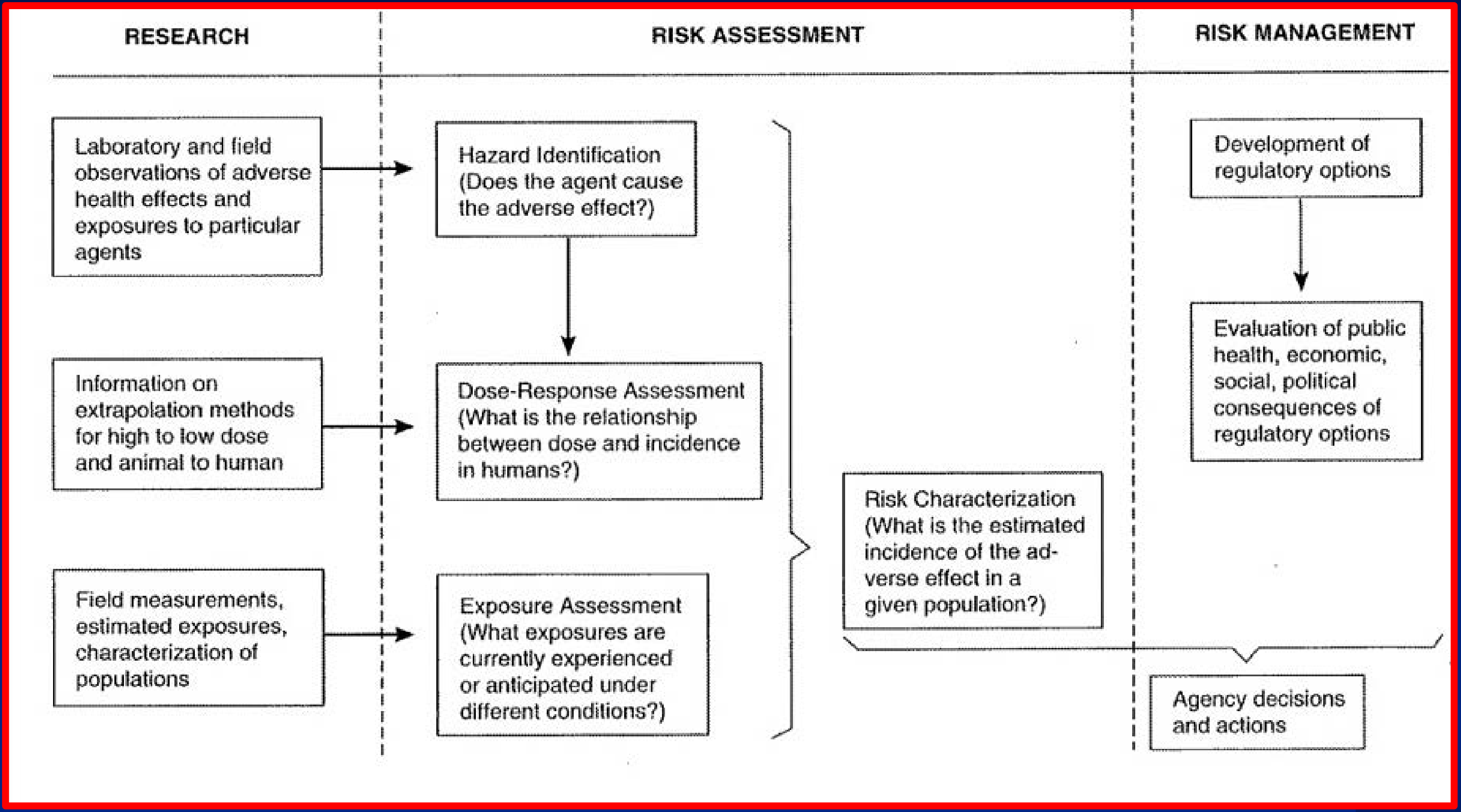
**NRC Strategic Plan (NUREG-1614, v6, 2014)

U.S. Nuclear Power Plants



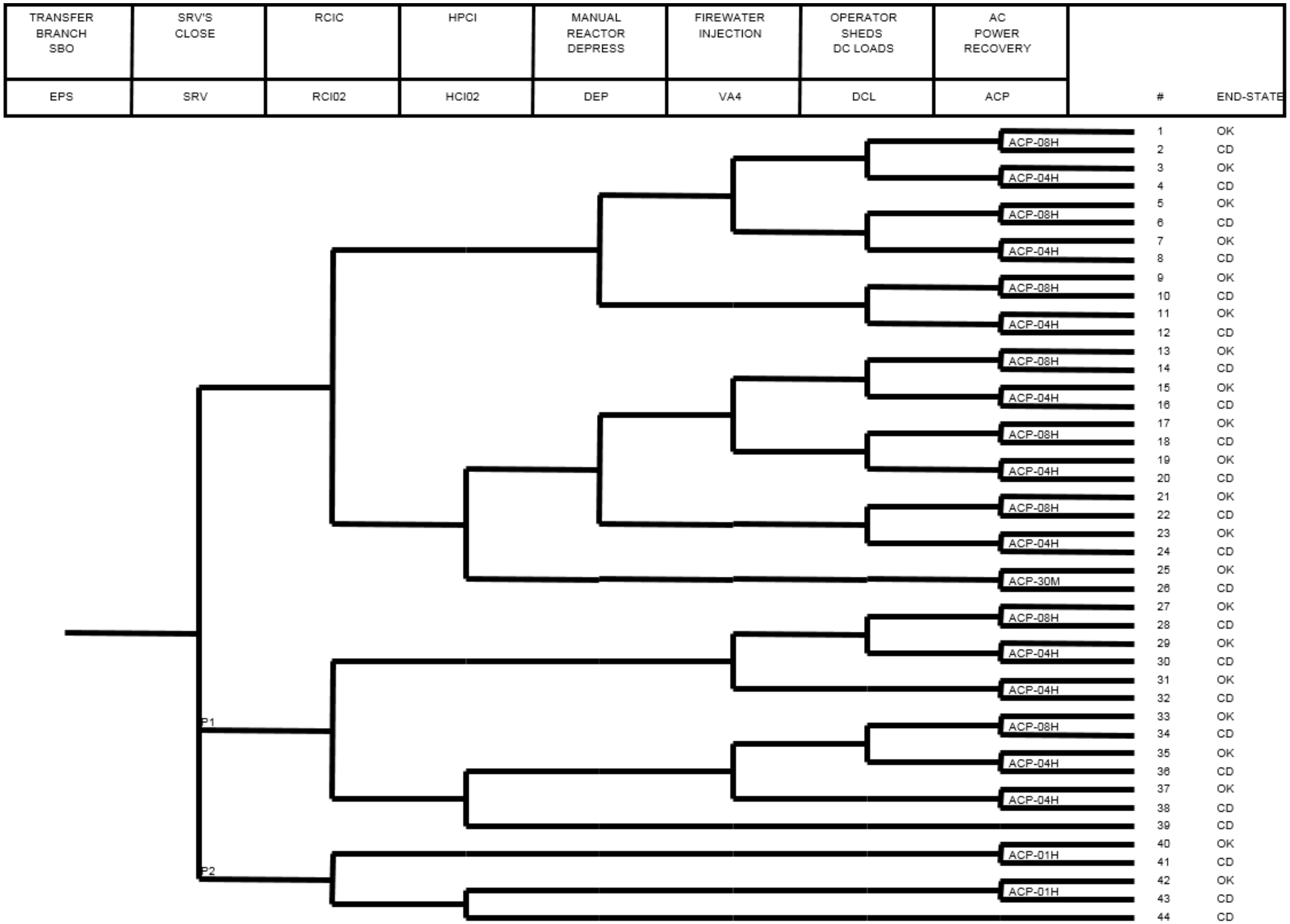
- 99 plants (61 sites)
- ~99,000 MWe, ~789,000 MW-hr (2013) = 19% U.S. total
- Worldwide: 435 plants, 372 GWe capacity

Risk Assessment vs. Risk Management



From National Research Council, "Understanding Risk: Informing Decisions in a Democratic Society," National Academy Press, 1996.

Example Event Tree



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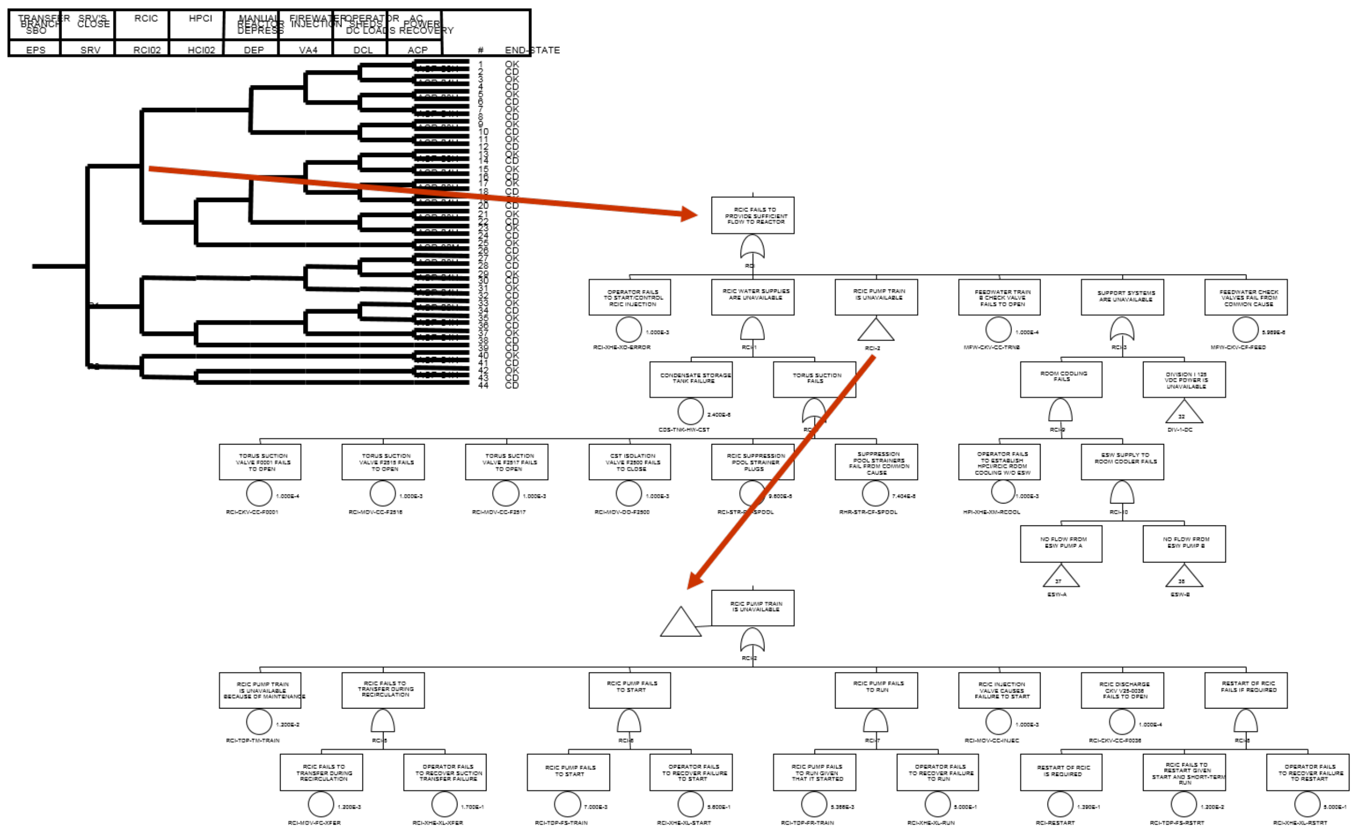
Example Fault Tree

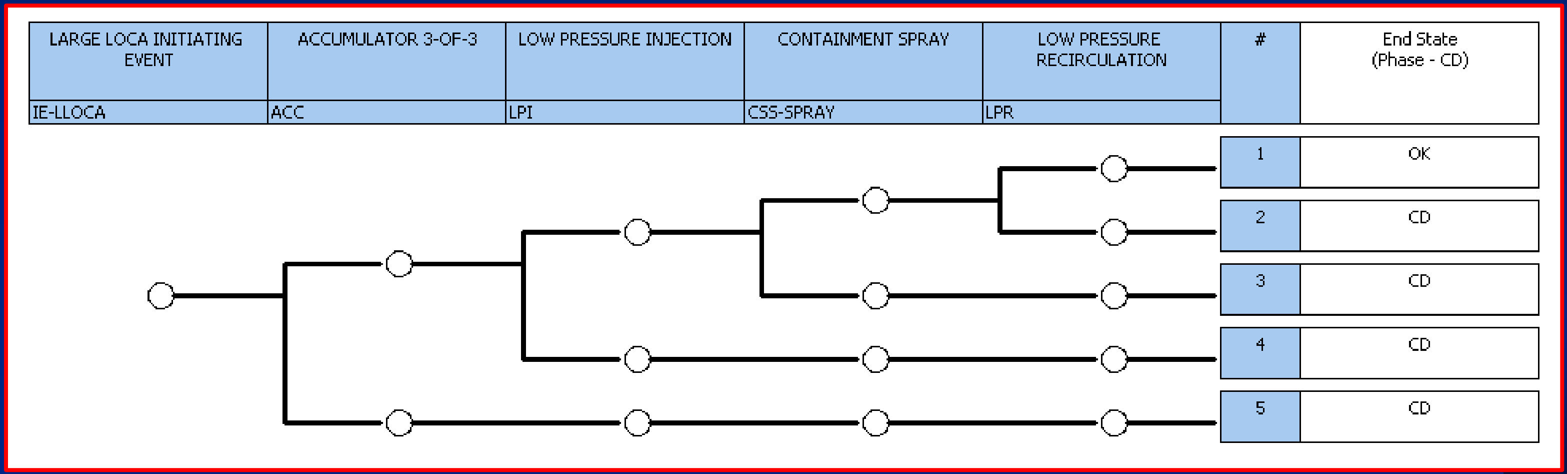


NRC PRA Models and Tools

- SPAR* Models
  - 79 operating plant models (event tree/fault tree)
  - 4 new reactor plant models
- SAPHIRE** code
  - Idaho National Laboratory (NRC-sponsored)
  - Features to support event and condition analysis

*Standardized Plant Analysis Risk

**Systems Analysis Programs for Hands-on Integrated Reliability Evaluation



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Risk-Informed Regulations

- Backfitting (10 CFR 50.109)
- Station blackout protection (10 CFR 50.63)
- Maintenance management (10 CFR 50.65)
- Combustible gas control (10 CFR 50.44)
- Fire protection (10 CFR 50.48)
- Reactor pressure vessel protection (10 CFR 50.61a)
- Special treatment of structures, systems, and components (10 CFR 50.69)
- New reactor certification and licensing (10 CFR 52.47)

Risk-Informed Licensing

- Changes in plant licensing basis
- Environmental reviews
- Application of risk-informed regulations

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Risk-Informed Oversight

- Reactor oversight process
- Incident investigation
- Enforcement discretion

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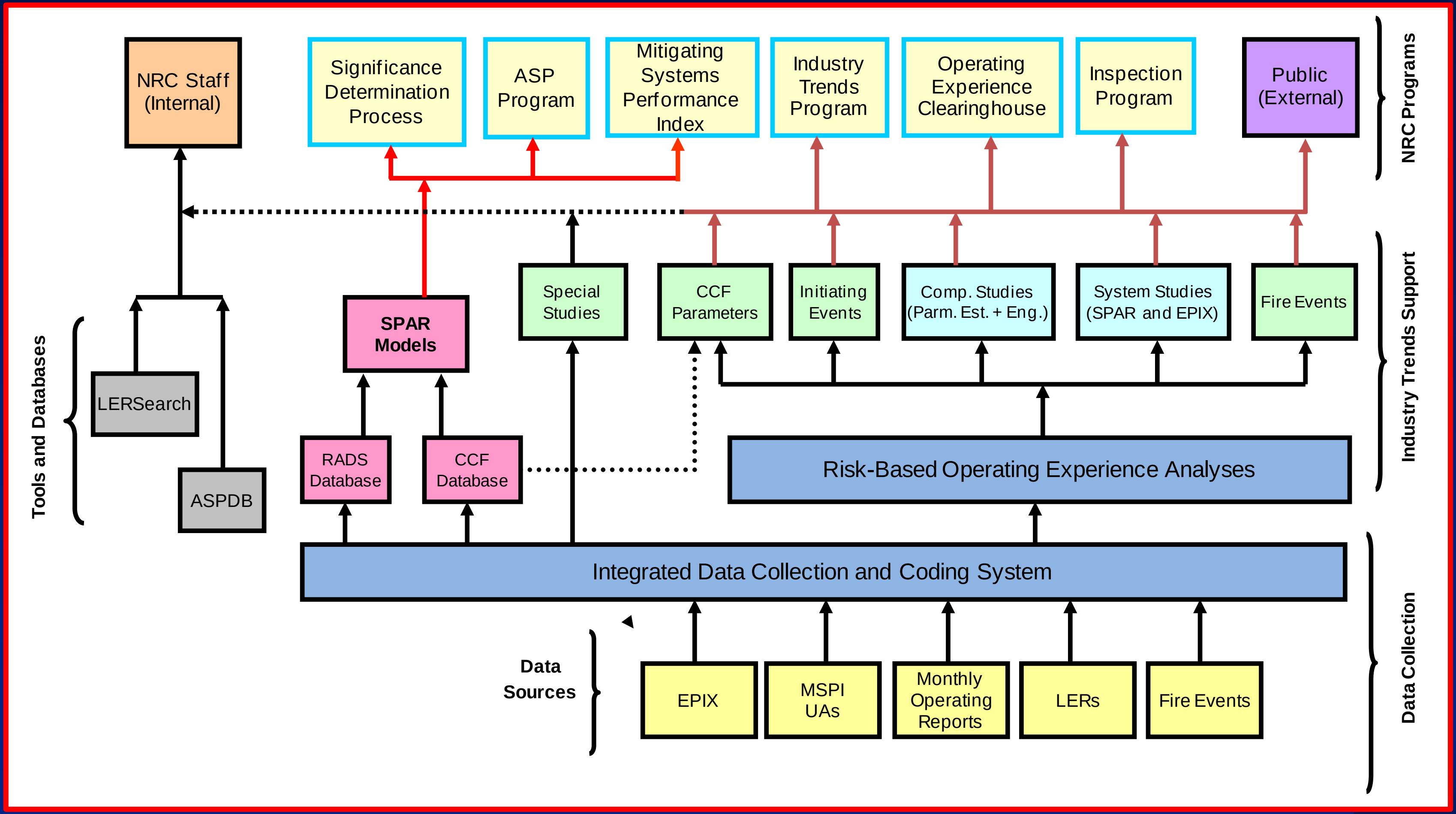
Risk-Informed Operational Experience

- Accident precursors
- Emergent issues
- Generic issues

Operating Experience Data



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Some Fire-Induced "Near Misses"

Event	Summary Description*
Browns Ferry (BWR, 1975)	Multi-unit cable fire; multiple systems lost, spurious component and system operations; makeup from CRD pump
Greifswald (VVER, 1975)	Electrical cable fire; station blackout (SBO), loss of all normal core cooling for 5 hours, loss of coolant through valve; recovered through low pressure pumps and cross-tie with Unit 2
Beloyarsk (LWGR, 1978)	Turbine lube oil fire , collapsed turbine building roof, propagated into control building, main control room (MCR) damage, secondary fires; extinguished in 22 hours; damage to multiple safety systems and instrumentation.
Armenia (VVER, 1982)	Electrical cable fire (multiple locations), smoke spread to Unit 1 MCR, secondary explosions and fire; SBO (hose streams), loss of instrumentation and reactor control; temporary cable from emergency diesel generator to high pressure pump
Chernobyl (RBMK, 1991)	Turbine failure and fire, turbine building roof collapsed; loss of generators, loss of feedwater (direct and indirect causes); makeup from seal water supply
Narora (PHWR, 1993)	Turbine failure, explosion and fire, smoke forced abandonment of shared MCR; SBO, loss of instrumentation; shutdown cooling pump energized 17 hours later

*See NUREG/CR-6738 (2001), IAEA-TECDOC-1421 (2004)

Operational Experience – Blayais

- 12/27/1999 – Storm during high tide in Gironde River estuary
- Overtopping of protective dyke
- Loss of
  - Offsite power (Units 2 and 4) – wind
  - Essential service water (Unit 1, Train A), low head safety injection and containment spray pumps (Units 1 and 2), site access – flooding
  - Site accessibility
- Papers in 2005 IAEA workshop following Indian Ocean tsunami
- Presentation at 2010 USNRC Regulatory Information Conference
- Little notice in PSA community

E. De Fraguier, "Lessons learned from 1999 Blayais flood: overview of EDF flood risk management plan," U.S. NRC Regulatory Information Conference, March 11, 2010.

Potential PRA Technology Challenges Revealed by Fukushima*

- Extending PRA scope
  - Multiple sources
  - Additional systems
  - Additional organizations
  - Post-accident risk
- Treating feedback loops
- Reconsidering intentional conservatism
- Treating long-duration scenarios
  - Severe accident management
  - Offsite resources
  - Aftershocks
  - Success criteria
- Improving human reliability analysis
  - Errors of commission
  - Severe accident management
  - Psychological effects
  - Recovery feasibility and time delays
  - Uncertainty in actual status
  - Cumulative effects over long-duration scenarios
  - Crew-to-crew variability
- Uncertainty in phenomenological codes
- Increasing emphasis on "searching"

*From Siu, N., et al., "PSA Technology Challenges Revealed by the Great East Japan Earthquake," PSAM Topical Conference in Light of the Fukushima Dai-Ichi Accident, Tokyo, Japan, April 15-17, 2013. (ADAMS ML 13099A347 and ML13038A203)